The legacy of Henri Victor Regnault in the arts and sciences

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Abstract: The 21st of July 2010 marked the bicentennial of the birth of Henri Victor Regnault, a famous French chemist and physicist and a pioneer of paper photography. During his lifetime, he received many honours and distinctions for his invaluable scientific contributions, especially to experimental thermodynamics. Colleague of the celebrated chemist Louis-Joseph Gay-Lussac (1778-1850) at the École des Mines and mentor of William Thomson (1824-1907) at the École Polytechnique, he is nowadays conspicuously absent from all the textbooks and reviews (Hertz, 2004) dealing with thermodynamics. This paper is thus the opportunity to recall his major contributions to the field of experimental thermodynamics but also to the nascent field, in those days, of organic chemistry. Avid amateur of photography, he devoted more than twenty years of his life to his second passion. Having initially taken up photography in the 1840s as a potential tool for scientific research, he ultimately made many more photographs for artistic and self-expressive purposes than scientific ones. He was a founding member of the Société Héliographique in 1851 and of the Société Française de Photographie in 1854. Like his scientific work, his photography was quickly forgotten upon his death, but has begun to attract new respect and recognition.

Keywords: Henri Victor Regnault, organic chemistry, thermodynamics, paper photography.

Introduction

Henri Victor Regnault (1810–1878) (see Figures 1a & 1b) was undoubtedly one of the great figures of thermodynamics of all time. His contributions to experimental thermodynamics and to organic chemistry were of great quality and have still a large impact today. Also a pioneer of paper photography, Regnault was born the same year as the physiologist Theodore Schwann, who designed the first rebreather, and famous artists like the composer and pianist Frédéric Chopin, the composer Robert Schumann and the playwright and poet Alfred de Musset.

From a political point of view, the 19th century was a stormy period in France, with the establishment of the Empire in 1804, the Restoration of the Bourbons in 1815, the July Monarchy in 1830, the Second Republic in 1848, the Second Empire in 1852 and the Third Republic in 1870. But it was also a period when great hopes were placed in science and especially in thermodynamics. The beginning of the 19th century had thus passed through a phase of tremendous discoveries thanks to scientists like Augustin Fresnel (1788-1827), André-Marie Ampère (1775-1836) or Nicolas-Léonard Sadi Carnot (1796-1832). The rest of the century was marked by important advances and remarkable experimental achievements in the field of thermodynamics. Nicolas-Léonard Sadi Carnot, the "father of thermodynamics", published a paper in 1824 entitled *Réflexions sur la puissance motrice du feu et sur les machines propres à développer cette puissance*, considered as the starting point of thermodynamics as a modern science, although the term "thermodynamics" would only be introduced in 1849 by William Thomson (Lord Kelvin).

Figure 1: (a) Henri Victor Regnault painted by his cousin, Eugène Amaury-Duval; (b) self-portrait of Henri Victor Regnault.

Henri Victor Regnault was considered in his time as one of the most talented experimenters in thermodynamics. Many students, who became later famous scientists such as the physicist Jean Bernard Léon Foucault (1819-1868), the chemist Robert Wilhelm Bunsen (1811-1899), the botanist Georges Ville (1824-1897) or the physiologist Jules Reiset (1818-1896) received some training in the laboratory of Regnault at the Collège de France. Mentor of the Scottish physicist William Thomson during the years 1845-46 at the École Polytechnique and colleague of Louis-Joseph Gay-Lussac (1778-1850) at the École des Mines, he is the only scientist of the 19th century to be the recipient of the Rumford and Copley medals awarded by the Royal Society and the Matteucci Medal. He obtained the Rumford medal in 1848 for his experiments to determine the laws and the numerical data, which enter into the calculation of steam engines, sharing this honor with Michael Faraday (1846), Georges Gabriel Stokes (1852) and Louis Pasteur (1856) among others. In 1863, he was made Commander of the Legion of Honor. Some years later, in 1869, he received the Copley medal for the second volume of his *Relation des éxperiences pour déterminer les lois et les données physiques nécessaires au calcul des machines à feu*, including his elaborate investigations on the specific heat of gases and vapours, and various papers on the elastic force of vapours. In 1875, he received the Matteucci Medal from the Italian Society of Sciences, sharing that honor with Lord Kelvin (1876), Lord Rayleigh (1894) and Albert Einstein (1921), for examples. He was also elected to numerous scientific societies, including the French Society of Physics in 1838, the French Academy of Sciences (in the chemical section, to the former seat of Pierre Jean Robiquet, 1780-1840) in 1840, the Royal Swedish Academy of Sciences in 1851, the Royal Society of London in 1852, the American Academy of Arts and Sciences in 1855, the American Philosophical Society in 1865 and the

Collège de France in 1872. He became also President of the French Academy of Sciences in 1855.

Though he received many honours during his lifetime, he is today undoubtedly the least well-known of all his contemporaries such as Joseph Fourier (1768-1830), Nicolas-Léonard Sadi Carnot (1796-1832), Émile Clapeyron (1799-1864), Julius von Mayer (1814-1878), Hermann von Helmholtz (1821-1894), Rudolf Clausius (1822-1888), Ludwig Boltzmann (1844-1906), James Prescott Joule (1818-1889), William Rankine (1820-1872), James Maxwell (1831-1879) or Willard Gibbs (1839-1903). Few traces of Henri Victor Regnault remain today. His name was inscribed on the Eiffel Tower by Gustave Eiffel in 1889, along with those of seventy-one other French scientists and engineers in recognition of their contributions. The crater Regnault on the Moon is also named after him. In 1881, Jean-Baptiste Dumas (1800-1884), perpetual secretary of the Academy of Sciences, ended his tribute to his colleague Henri Victor Regnault with the hope that, one day, "*la science et la nation payent, enfin, leur dette à sa mémoire digne de tous les honneurs*". The bicentennial of his birth is then the opportunity to tell his life and legacy in sciences but also in the art of photography, to which he not only contributed his double expertise in chemistry and optics, but also some of the most splendid photographs of the century.

Life and Career

Henri Victor Regnault was both a remarkable chemist and physicist but also a well-known photographer. He was born in Aachen (now in Germany) the 21st of July 1810. His father André Privat Regnault, who was captain in the corps of civil engineers in Napoleon's Imperial Corps, died in 1812 on the road of Wilna during the Russian campaign. Six years later, at the age of eight, Victor and his younger sister moved to Paris after the death of their mother, Marie-Thérèse Massardo. They were taken in by a comrade-in-arms of their father, Jean-Baptiste Clément. His wife, who was the daughter of Alexandre Duval, member of the French Academy, became like a second mother for the two orphans. To provide for himself and his sister, Victor worked as a clerk for a drapery firm, *le Grand Condé*, until he was eighteen. He spent all his spare time at the National Library and showed an early aptitude for mathematics.

He rapidly entered in a preparatory institution for the prestigious École Polytechnique. Although suffering from the fevers of an unnamed illness at the time, he passed the admission exam in 1830 after a memorable verbal joust with his examiner Etienne-Louis Lefébure de Fourcy (1787-1869), placing 54th among the 126 entering students. His superiority eventually obtained him a salaried position there as assistant lecturer, which also enabled him to establish a dowry for his sister. He remained two years at École Polytechnique, where he graduated first in his class, in spite of a severe injury at his left eye due to some pieces of a glass lamp. Two celebrated chemists and teachers at the Ecole, Louis-Joseph Gay-Lussac (1778-1850) and Pierre-Louis Dulong (1785-1838) would have a great influence on his future works. He had also Claude Louis Marie Henri Navier (1785-1836) as professor in mechanics, Dominique François Jean Arago (1786-1853) or Félix Savart (1791-1841) in machines among others.

Regnault entered the École des Mines, one of the applied schools, the 15th of September 1832. He completed his regular three-year course of study in only two years and left it the 20th of February 1834 after having achieved first class rank. He received excellent marks, with especially high levels in chemistry and drawing. In spite of that, he was not permitted to graduate. He had to do two internships abroad before getting his final diploma. Thus, in 1834, he traveled first to Belgium and then to Germany (the Harz region) to study silvermining techniques. In 1835 he did a second trip to Würtemberg in southwestern Germany and then to Switzerland to analyse the salinity of thermal waters. In Saxony, he visited coal mines and other industrial sites to better understand the metallurgic process. He also stopped briefly to study in the famous laboratory of Justus Von Liebig (1803-1873) in Giessen. He wrote four memoirs available in the library of École des Mines about the coal mines close to Aachen, the mines and factories in Harz… (see in Regnault 1834).

In 1835, the administrators of the Ecole des Mines designated Regnault to fill a position in Rive de Gier, in the nearby of Lyons. They reversed their decision only two weeks later and appointed Regnault as a laboratory assistant of Pierre Berthier (1782-1861). On November 25th, 1835, Regnault was definitively attached to the chemical laboratory of the École des Mines. There he was named assistant Professor of docimasy, replacing the full Professor Pierre Berthier (1782-1861). During Spring 1836, he was granted a three month leave to go to Lyons to fill in for Jean-Baptiste Boussingault (1802-1887), Professor at the Faculty of Science. Finally, he obtained his engineer's diploma, just after his return from Lyons, the 19th of June 1836 after having submitted the statement of this second trip abroad. The same year, he married Clémence Clément, the daughter of his surrogate parents. At the École des Mines, he distinguished himself in the nascent field of organic chemistry by synthesizing several chlorinated hydrocarbons. Among others, we can cite his researches on the action of chlorine upon ether and upon the chlorides of ethyl and ethylene. His results were published in eighteen memoirs in the *Annales de Chimie et de Physique* between 1835 and 1840. In February 1838, he was appointed Professor of assaying and assistant Director of the Ecole des Mines's laboratory.

Regnault was candidate for the position of *répétiteur* for Gay-Lussac. This latter wanted Auguste Laurent (1807-1853) as collaborator but he should submit to the final decision of the Council of Public Instruction, which unanimously favored Regnault. He held then now two positions, one at the Ecole des Mines and one at the Ecole Polytechnique, where he began to take over some lectures of Gay-Lussac. When Gay-Lussac retired as Professor of chemistry on November 18, 1840, Regnault was recommended as his successor by the Academy of Sciences on December 11, 1840. He was then appointed Professor and named to Gay-Lussac's coveted chair of chemistry at the École Polytechnique. Afterwards, he became Professor of physics at the Collège de France (1841), succeeding Félix Savart (1791-1841) as the Chair of general and experimental physics. There, he began his life's work in physics by studying the specific heats of elements and compounds. In 1843, he was commissioned by the Minister of Public Works to compile extensive tables on the properties of steam valuable for steam engineers. In 1847, he published these results in a 767-page article entitled *Relations des expériences ... pour déterminer les principales lois et les données numériques qui entrent dans le calcul des machines à vapeur*, as vol. XXI of the Memoirs of the Academy of Sciences. For this paper, which also stimulated William Rankine to develop his theories of thermodynamics and his molecular vortex hypothesis, Regnault received the Rumford Medal of the Royal Society of London and was appointed as chief engineer at the École des Mines.

Regnault was, like many other scientists in this time, captivated by the promise of photography as a valuable tool to investigate in more details empirical science. He applied his talent of meticulous experimenter to refine the inexact practices of photography. Charged by the Académie, he studied, in particular, the modifications of Louis Désiré Blanquart-Evrard to William Henry Fox Talbot's positive/negative calotype paper process in April 1847. He contributed at least fourteen paper negative photographs to Blanquart-Evrard’s Imprimerie Photographique Editions in the early 1850’s. With other artistic and scientific figures, he founded the Société héliographique in 1851, to which he consecrated a lot of his energy. When that organization folded in 1854, some of its members formed a new photographic institution, the Société française de photographie, unanimously electing Regnault as their first president in 1855. He was also elected as a foreign member of the London Photographic Society (later, the Royal Photographic Society).

On April 12, 1852, Regnault was appointed Director of the state-owned Manufacture Impériale de porcelaine de Sèvres by Charles-Louis Napoléon Bonaparte, succeeding his classmate at the Ecole des Mines, Jacques-Joseph Ebelmen (1814-1852). He moved to Sèvres during spring with his wife, their four children, his mother in law and two sisters in law. There, he combined his administrative duties at the Manufacture with his teaching and research at the Collège de France. At Sèvres, he oversaw several improvements in the manufacture of porcelain (Reif-Acherman 2010). He continued also to work on the thermal properties of different matters. He designed sensitive thermometers, hygrometers, hypsometers, calorimeters, which Sèvres artisans helped fabricate. He measured the specific heats of many substances and the coefficient of thermal expansion of gases. The direction of the factory lasted from 1852 to 1871 and during this period, his scientific and photographic careers were closely linked. During his directorship, he was in charge of maintaining the artistic reputation of the Manufacture, while modernizing the industrial techniques. His great knowledge in chemistry enabled him for example to rediscover the formula of a soft paste, an artificial porcelain displayed during the 16th century at the Medici Court. At the suggestion of his *chef d'atelier*, Louis-Rémy Robert (who was also a photographer), Regnault established a photographic department in the Sèvres factory in 1863 with the aim of introducing the new photographic techniques (photoceramic techniques, vitrifiable photography) in the manufacturing of the porcelain.

In August 1856, he suffered a severe fall in his laboratory, which threatened his life for more than a month with especially a twelve-day’s coma, and it appeared that he never made a full recovery. From this time on, the good fortune of the previous decade seemed to evade him.

The year 1866 was particularly harsh, in which his wife, his wife's mother (Ms. Clément), and two other members of his family died, leaving Victor alone with four children, three of whom showed signs of mental illness. In 1870, during the siege of Paris, Prussian soldiers destroyed his laboratory, which contained his unique collection of scientific instruments and reams of unpublished research. The final blow came on January 19, 1871, when his son Alex-Georges-Henri Regnault, a celebrated painter, was killed at the Buzenval battle, on virtually the last day of the war.

Regnault immediately left Sèvres with his oldest son Léon interned in an asylum and his other children also suffering from mental illness to convalesce in a small French town Lassigneu, near Geneva. There, he tried to reconstruct his laboratory and return to research, spending some time with his previous Swiss student Jacques-Louis Soret (1827-1890). Few times later, his sister, who spent also some time in Lassigneu to aid him, suffered a sudden attack and reputedly died in his arms. This final tragedy precipitated a stroke of apoplexy in 1873. He returned from Switzerland, but retired from science, with his final years of infirmity being spent under the care of Jules de Reiset, a former colleague, Mme. Serais, a family friend, and Lord de Belley. He died the 19th of January 1878.

Readers can refer to the tributes of Dumas (1881), de Lapparent (1897) or le Chatelier (1911) for biographies (in French) of Henri Victor Regnault.

A Meticulous Chemist

Regnault did all his work of chemistry both at the laboratory of the École des Mines in Paris, under the eyes of his chief and former Professor, Pierre Berthier, the author of the famous *Traité des essais par la voie sèche* (1834) and also at the Ecole Polytechnique. He acquired from his mentor an absolute respect for experimentation and a major contempt for vain theories, which remained the two essential characteristics of all his work. From 1835 to 1840, Regnault published his work in eighteen memoirs of chemistry, without interruption, always taking care to publish innovative and accurate results. He wrote also a four-volume book entitled *Cours élémentaire de chimie,* published from 1847, considered in its time as the standard reference for teaching chemistry. The contribution of Regnault in chemistry is so important that only few representative works of Regnault are summed up in the following.

Major advances in organic chemistry (1835 - 1840)

He devoted his first personal research to chemistry and published his first memoir on the compound ethylene dichloride, called also the Dutch Liquor, in *Annales de Physique et de Chimie* (Regnault 1835). Justus Von Liebig (1803-1873) and Jean-Baptiste Dumas (1800-1884) had each analyzed the composition of Dutch Liquor and had found somewhat different results. This light dissension had left many chemists indifferent, but not Regnault, for whom there could be only one truth. His first concern was to operate on pure constituents, by controlling all the possible variables of the properties of the compound obtained. Regnault studied Dumas's process for the analysis of the organic matter by combustion with copper oxide, considering the causes of error particularly arising from the condensation of steam on this oxide. His final measurements showed Von Liebig's error and confirmed the correct analyses of Dumas. Regnault multiplied his experiments in order to find the results of Von Liebig's work, and thus managed to establish the role of the incomplete purification of the products studied by the German chemist. Regnault was not satisfied yet because he did not know the nature of the impurity contained in the analyzed body. Nevertheless, during the preparation of its compound, he had observed a violent effervescence, initially unexplainable. In fact, it was due to ethylene chloride, which gave birth, by hydrochloric loss of acid, to a still unknown gas body, chlorinated ethylene. This memoir is one of most important of organic chemistry because it presents a perfect example of the law of substitutions recently discovered by Dumas. Then, continuing its observations gradually, he published three memoirs relating to the action of chlorine on hydrocarbons and hydrochloric ethers, highlighting the existence of two parallel series of compounds substituted, isomer two to two, and showing in addition that substitution can respect the molecular grouping of the primitive compounds having been used as starting point. Among theses memoirs on the theory of substitutions we can cite the memoir entitled *De l'action du chlore sur les éthers hydrochloriques de l'alcool et de l'esprit de bois, et de plusieurs points de la théorie des éthers (1839).*

Regnault discovered also various organic chlorides which became important industrially, including vinyl chloride and carbon tetrachloride. Vinyl chloride was indeed first produced in 1835 by von Liebig and Regnault. They obtained it by treating ethylene dichloride with a solution of potassium hydroxide in ethanol. Three years later, Regnault accidentally discovered Poly-vinyl chloride (PVC), made by polymerization of vinyl chloride monomer. Its white solid powder was obtained after the exposure of gaseous vinyl chloride (CH_2CH-Cl) to sunlight. Regnault knew almost nothing about this chemical reaction and the composition of this product. It remained unpublished until Von Liebig's paper of 1878. PVC is now one of the most explored polymers in the world, bearing a wide range of properties, which explains its use in many applications, such as pipes, packaging, sheets, flooring, medical equipment, and containers of many kinds.

One other important contribution of Regnault to organic chemistry was a series of researches in 1837 on alkaloids and organic acids (Regnault 1837c). He introduced a classification of the metals according to the facility with which they or their sulphides are oxidized by steam at high temperatures (Regnault 1837a). The experiments, which were undertaken in order to check the exactitude of the classification of Thénard, had great repercussions at the time. The same year, he published a study on the mineral fuels depicting the properties and constitution of coals and the year after, on organic alkalis. He also took samples of atmospheric air from different parts of the world and demonstrated that wherever it comes from it contains about 21% of oxygen. He worked also in the field of mineralogy with some works on binary alloy and mica and in the field of metallurgy by his process of carbon mixture in cast iron (1837b).

The Professor of chemistry (1840 - 1870)

The fertile activity of Regnault explains the young engineer's remarkably fast-growing reputation. In 1840 he was recalled to Paris by his appointment to the chair of chemistry in the École Polytechnique and also by his appointment, on July 6, 1840, to the Academy of Sciences. He entered the section of chemistry to replace Pierre Jean Robiquet (1780-1840). His election was confirmed by Royal Decree on July 20, 1840, making him the youngest member in the chemistry section of the Academy. The amount of work provided at that time by Regnault was amazing but he gave up definitively all research of chemistry. He continued nevertheless to deal with the teaching of this science during thirty years at the École Polytechnique as substitute for Gay-Lussac. In addition to the monitoring of students at the laboratory of the Ecole des Mines, he taught analytical chemistry there in Berthier's former position. During this period, he also authored reports on some very different topics. For example, he published in 1841 a report on the Marsh process, used to detect the presence of arsenic in liquors and gases (Regnault 1841b).

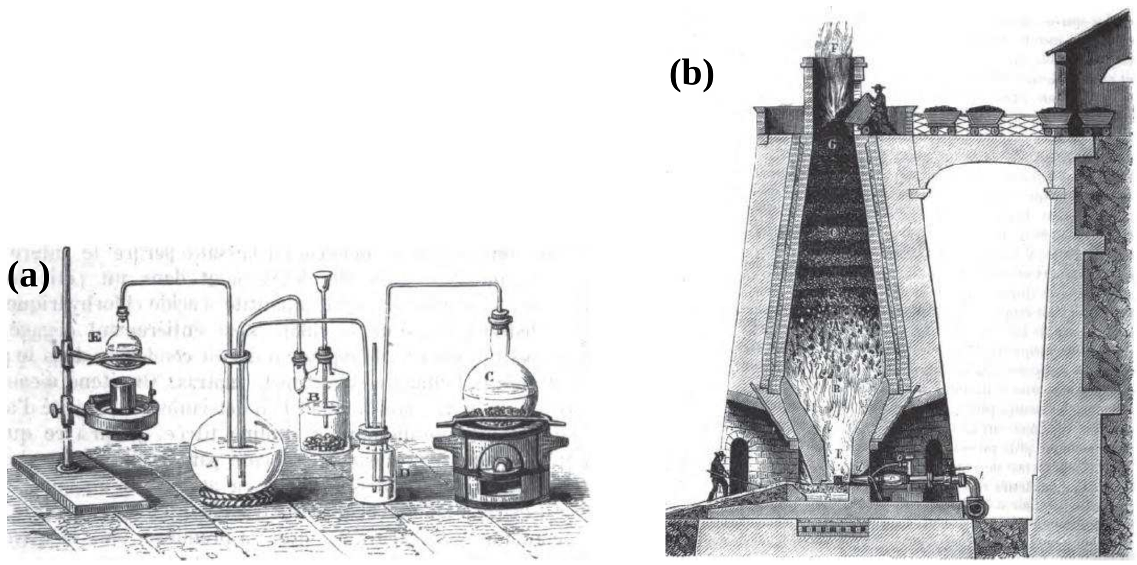

Figure 2: Sketches after the 5th Edition of “Cours élémentaire de chimie, tome 3” (1858), available free online: (a) experimental set-up to test the oxides of manganese; (b) regular work in a blast-furnace.

In 1847, he began the publication of his four-volume *Cours élémentaire de chimie*, and in 1849 that of the small volume entitled: *Premiers éléments de chimie*. For the next twenty-five years, these two works formed entire generations of French chemists. In only 20 years, 25 500 copies of the *Cours élémentaire de chimie* and 26 000 copies of the *Premiers éléments de chimie* (Editor Victor Masson) were sold, which made them "bestselling" scientific books by today's standards. It would be difficult to find another work of scientific pedagogy of equal success. This success is due first to the fact that they were the first works of chemistry written expressly for teaching. In the edition of 1847, one finds a particularly high level discussion of the theory of equilibrium between the carbon oxide and iron oxide. We also find for the first time a complete statement of the famous Berthollet laws. Regnault's *Cours élémentaire de chimie* was also a real revolution: for the first time, very clear illustrations printed within the text, instead of at the end of the volume where they would be difficult to consult (see two examples in Figure 2). These books were translated in many languages and passed through many editions. In spite of their importance, the *Cours élémentaire de chimie* and *Premiers éléments de chimie* are nowadays completely unknown to young chemists and are even difficult to find in our best scientific libraries.

The Parisian Company of Gas (1852 - 1870)

Regnault also took part in the creation of the Parisian Gas Company, where he was the scientific consultant of the Company for twenty years. In 1852, gas was manufactured in Paris by a half-dozen independent companies, and talks were underway for the renewal of their concessions. The Emperor, wishing to keep his promise to deliver affordable gas to Parisians, charged Regnault with making experiments to determine the real cost price of gas. An experimental factory was built in Saint-Cloud, near the manufacture of Sèvres. Always concerned about the accuracy of the measurements but not being able to spend all his day to the factory, Regnault even requested Imperial soldiers to guard the experiments. Each morning, he came to sweep the factory and weigh the coal intended for the tests of the day, placing an armed sentinel at each door, with instruction to allow nothing to enter or leave. He returned in the evening to measure the produced gas and to weigh the by-products. He found that the price could be divided by a factor of five, compared to the price proposed by the Companies. His report was violently attacked by the interested parties, with Emile and Isaac Péreire protesting to the Emperor, while still accepting Regnault's results. According to them, the rise in the current price of gas was due to overhead costs and the expenses of interest on capital. They agreed to reduce this price with a sufficiently prolonged concession and were allowed to amalgamate the Companies into a single corporation. They proposed to immediately lower the price of gas to 30 centimes and to share the benefit with the consumer after 1870. An agreement was signed in March of 1857 and Regnault was named consulting engineer of the new Parisian Company of Gas, for which he received generous compensation. Regnault also created the experimental factory at la Villette, devoted to the industrial improvement in the manufacture of gas. He also dealt with the treatment of tar and the processes of heating. He also worked with Sir William Siemens (1823-1883) on the application of his new furnaces to the manufacture of gas. He was interested particularly in the use of coke in domestic heating, correcting the drawings of the apparatuses put on sale by the Company, and promoting coke as a better fuel. Thanks to Regnault, from 1857 to 1870, the Parisian Company was thus the starting point for all improvements in the gas industry, including a huge increase in efficiency of up to 300 cubic meters per ton, use of the furnaces with recovery, precipitation of the last blisters of tar by impact tampers, treatment of tar by split distillation, application of coke to domestic heating in apparatuses using rational combustion, and the exact determination of the lighting power of gas…

In 1857, Regnault and Dumas were charged with seeking the most accurate means of measuring gas. Formerly, it was measured only by the glare of its flame. In 1860, they led to a purely conventional definition of the lighting power considered as being a specific property of gas: one limits to 105 liters per hour the gas expenditure necessary to produce in a well defined Bengel nozzle, a luminous source of the same intensity than the Carcel lamp burning 42 grams of oil per hour. Their work was completed in 1860. Hereafter, the French municipalities introduced into their specifications the control of gas by the method known as of Dumas and Regnault. It is fully explained in the discourse of Emile Sainte-Claire Deville (1910), Regnault's last student.

The heritage of Regnault in thermodynamics (1841-)

The transition from chemistry to physics was due in fact to several circumstances. Firstly, his experiments on specific heats served clearly as a bridge between these two periods of his life. Secondly, he was appointed Professor of experimental physics at the Collège de France on April 27, 1841 by the Academy of Sciences, after the death of Félix Savart. In August of the same year, he moved with his family into an apartment located one floor above his laboratory at the Collège de France. There, he was the neightboor of Jean-Baptiste Biot (1774-1862), Professor of Mathematical Physics, which might have launched his career in experimental thermodynamics. In this field, he published an incredible number of memoirs in the *Annales de Chimie et de Physique* and most of all three memoirs on steam engines and their numerics. His main works concerned the expansion of gases and dry vapours under different experiment conditions, the density of gases, the weight of a litre of air and other gases, the measurement of temperatures, the absolute dilatation of mercury, the law of compressibility of elastic fluids and liquids, the elastic forces of vapours, the latent heat of vapours or the specific heat of water and elastic fluids, among others.

Specific heat of elements and compounds,

As suggested by Dumas, Regnault pursued his researches on the specific heat of elements and compounds (gases, liquids or solids) seeking, in particular, an universal law for the specific heat of solids. He performed numerous experiments using different methods and apparatuses. The three methods used (ice-fusion method, cooling method and mixture method) were all based on the establishment of thermal equilibrium between two systems at different temperatures. After having identified the sources of errors for each method, he preferred to use the method of mixtures.

His first results on the specific heat of solids were presented to the Academy of Sciences on April 3, 1840 (Regnault 1840). One finds there the first experimental demonstration of the approximate law of Dulong and Petit, which had been hypothesized, rather than established, by these physicists. For 24 pure elements, Regnault demonstrated that this law was only partially true mostly because there was no accepted table of atomic weights at that time. In 1841, Regnault published a memoir on the specific heat of compounds (metallic alloys, sulphides, organic salts…), which contributed to the reputation Regnault as a chemist (Regnault 1841a). He showed that “the specific heats of all compound substances having the same atomic composition and similar chemical constitution are in inverse proportion to their atomic weights".

François Delaroche (1780-1813) and Jacques-Etienne Bérard (1789-1869) believed that the specific heats of gases at constant volume and pressure depended on temperature, which motivated the work of Regnault on the specific heats of gases. He then undertook experiments in 1843 with liquids and gases. The specific heat of carbonic acid increases for increasing values of temperature, which is not the case for air. He concluded that all gases, which follow the Boyle-Mariotte's law, have a constant specific heat, whereas all other gases, vapours, liquids and solids have an increasing specific heat, when the temperature also increases. He concluded from all his experiments, that all laws on the specific heats of gases had no direct applications as they were valid only for ideal gases. During his entire career, he continued to work on the specific heat of elements and compounds (see in particular Regnault 1843b, 1861) and especially on water and some elastic fluids like oxygen, nitrogen, hydrogen or chlorine. He demonstrated also that the hypothesis of Amedeo Avogadro (1776-1856) saying that the atomic heat of a compound is the sum of the atomic heat of its constituents became invalid when the complexity of the gaseous compounds increased.

The experiments of Regnault were indeed highly accurate but they suffered also from several weaknesses. His apparatuses were often complex, requiring thus many assistants and a huge amounts of elements and compounds to investigate. Many of them are sketched in the book of Jamin (1859). The experimental procedures required also a long time to heat the element, then to reach the thermal equilibrium and to place accurately the measurement apparatuses. The experimental procedures induced different sources of errors. Regnault suspected that the chemical structure of solids was altered during heating as well as the specific heat of porous substances by the moistening.

The three memoirs on steam engines (1847)

An event of crucial importance diverted the career of chemist of Henri Victor Regnault and marked the beginning of a great career in experimental thermodynamics. The French Ministry of Public Works, concerned about the rapid development of steam engines, thought it would be useful to publish a report on that subject. In 1823, Arago and Dulong were first designated by the Paris Academy of Sciences as the co-leaders of the commission in charge of this report. Due to numerous administrative difficulties, the report was not achieved. Thus, a new commission was appointed in 1843 with Regnault as chief. The goal of this second campaign was the publication of a report specifying the conditions under which steam engines could be operated safely while increasing their efficiency. Regnault had to perform the experiments necessary for the determination of the numerical data entering in the calculations of the steam engines and to establish the main physical laws involved in their use. He evaluated also the uncertainty of the experimental data relating to the properties of steam. Having left the École des Mines for the Collège de France, he lacked a sufficient budget to complete its experiments; the French Ministry of Public Works thus allocated him an annual subsidy of 5.000 francs. This research, prolonged over twenty-five years, was extended to all fluids and led to great improvements, especially in the processes of pressure and temperature measurements and in the measurements of heat quantity. The huge amount of collected experimental data was published in 1847 in three volumes of more than 3200 pages in length and in the Memoirs of the Academy in a 767-pages paper. These results were used constantly for most of the century to validate scientific theories and in particular in thermodynamics. His main results on the expansion of gases and dry vapours, the density of fluids, the measurement of temperatures, pressures and hygrometry, the absolute dilatation of mercury, the law of compressibility of elastic fluids and liquids, the elastic forces of vapours, the latent heat of vapours or the specific heat of water and elastic fluids ... are all contained in this memoir. It has also been published in more than 50 papers. Given the amount of Regnault's results, only few points are developed in the following.

The use of highly accurate graphs

One interesting issue, which has been addressed by Jamin (1859) and more recently by Mendoza (2001), is how Regnault calculated the steam properties starting from his experimental measurements. During the final exam of the École des Mines, Regnault received distinction in both chemistry and drawing. His aptitude for drawing, together with his meticulousness, allowed him in 1847 to be the first to publish graphs of his measurements with accuracy better than one hundredth of a millimeter. He performed measurements of the absolute expansion of a column of mercury with temperature and also measurements of the vapour pressure of water over a large range of temperature to determine its latent heat of vaporization. The apparatus used for the first measurements is fully explained in the course of Jamin (1859). For each experiment, he performed several series of measurements changing the procedure or the apparatus in order to distinguish the systematic errors from the random ones. Then, he did not average all the data but selected the most reliable ones. After some unsuccessful tries with graphs on paper, he worked on a copper engraving plate, taking all measurements and fitting the curve directly on the plate. A section of the 80 cm x 80 cm print from the engraved copper plate can be found in the paper of Mendoza (2001). This author told in detail how Regnault drew the grid with a home-made machine and then plotted each measurement point. To fit his measurements of the absolute expansion of a column of mercury, he used a quadratic equation and from that equation, he calculated the tables.

Vapour pressure of steam

Henri Victor Regnault improved the method of Dalton to measure the elastic force of vapours at saturation. At the boiling point of a liquid, the elastic force of its vapour is equal to the supported pressure. Thus, if one boils water in an enclosure under increasing pressure conditions, water will reach increasing boiling temperatures at the same time. For each case, the elastic force of vapour will be equal to the imposed pressure. To represent his results and provide some experimental laws, he used the same procedure, engraving all his data on a copper plate… Tables have been later published by Aimé in 1845. Today, the most famous law of Regnault deduced from his huge amount of measurements is an empirical formula giving the latent heat of vaporization L_v (kJ/kg) of water as a function of temperature T (K):

$L_v = 3335 - 2.91\ T$, for temperatures in the range : $373.15\ K - 473.15\ K$. It is obtained using the value of the old calory calculated using the experiments of Rowland (Ekholm 1891). This equation is often used for the operating of autoclaves. It showed in particular that the theory of Southern and Creigton, who admitted that L_v was independent of T was wrong. All the results of his experiments on the vapour pressure of steam between 28.45°C and 148.26°C have been published in 1844. He published also some works on the latent heat of fusion of ice and provided useful tables (Regnault 1843a).

On the dilatation of gases

Regnault measured the increase of the elastic force of a gas, when it is brought to a higher temperature at constant volume assuming the Boyle-Mariotte's law. From this measurement, he was able to determine indirectly the dilatation of gases. Gay-Lussac stated three laws on the dilatation of gases. Firstly, all gases dilate equally. Secondly, their dilatation is independent of pressure and finally, the coefficient of dilatation of all gases is equal to 1.375 between 0 and 100°C. Dulong and Poisson proposed respectively the values 1.338 and 1.421 for air. Gustav Magnus (1802-1870) in Germany and Henri Victor Regnault in France were not convinced about that and, from 1841, they spent a lot of time using different methods to demonstrate that the value 1.375 was only approximately true. Regnault used three methods to study the dilatation of dry air. With the successive approximation method, which corresponds to a dilatation at a constant volume, he obtained 1.36645, which was somewhat different from the value 1.36706 obtained for a dilatation at a constant pressure. Regnault explained this difference by the use of the Boyle-Mariotte's law, which is not exactly true for the dilatation at a constant volume. Thus, the difference between the two approaches was real and the value 1.375 proposed by Gay-Lussac should be definitively replaced by the ones proposed by Regnault. He proceeded with many other experiments to investigate the dilatation at constant pressure, at constant volume, for different types of gases (hydrogen, air, sulphurous acid, carbonic acid…) and for different pressure levels. He finally showed that all gases dilate unequally. He also performed many measurements using different procedures (sudden or successive expansions) and in various geometrical configurations (capillarity tubes, orifice in a thin plate…). The reader can refer to the memoirs of Regnault on the expansion of gases (1842a, 1869).

Perfect gas limit and the absolute zero

The measurements of Regnault were also used to establish the state equation of perfect gas. In his memoir on Carnot cycles (1834), Emile Clapeyron combined the Boyle-Mariotte's law (1662) relating volume and pressure with the Gay-Lussac's law (1802) relating volume and temperature to obtain: $p\ v = R'\ (a + t)$, where $a=267$, t is the temperature in degrees centigrade and p and v are the absolute pressure and volume per unit mass respectively. Clausius proposed in 1850 another value of $a=273$ based on the experimental data of Regnault and then substituted the absolute temperature T in place of $(a + t)$, to obtain the well-known Boyle-Mariotte-Gay-Lussac law or nowadays the perfect gas law: $p\ v = R'\ T$, with $R' = R\ /\ m$ (m the mass of gas) and R the universal gas constant equal to 8.314 J/kg/K.

One question that remained: why did Clapeyron choose the letter *R* for this constant? This problem has been addressed recently by Jensen (2003). One theory is that this choice was arbitrary and the most probable reason was that *R* stood for *raison* or *rapport* (ratio in English), as *R* is obtained by the ratio between $(p\ v)$ and T. Jensen (2003) suggested that some scientists from IUPAC might have considered to name the symbol *R* for the ideal gas constant in honor of a famous scientist, in their opinion, Henri Victor Regnault, whose accurate experimental data were used by Clausius to correct the conversion factor between the centigrade and absolute temperature scales and to evaluate the value of *R*.

This last equation operates for perfect gases and not for real ones. Nevertheless, real gases approach the perfect gas limit when the pressure or density tends to zero. This topic received much attention, particularly from Regnault, who was aware of the difficulty to solve this problem experimentally. In a letter sent to William Thomson the 9th of May 1854, Rankine proposed a new expression for the equation of state for real gases, where the leading term is linear in density: $p\ v\ /\ (RT) = 1 + B\ /\ v + \ldots$, where B is the second virial coefficient proportional to the amount of gas and function only of the temperature. Rankine used some measurements of Regnault (1842) of the mean increase in pressure of a gas heated at constant volume in the range *0-100°C*. He extrapolated these results obtained for air and carbon dioxide to provide an estimate value of the zero of the perfect gas scale at zero pressure equal to *-274.6°C*. The measurements of Regnault of the expansion coefficient and the rate of increase of volume of a gas heated at constant pressure provided a better estimate of the absolute zero, which was confirmed by modern data as being equal to *-273.16°C*.

Innovative measurement apparatus

The perfection of the methodology of physical measurements took place rapidly between 1820 and 1840 by researchers like Karl Friedrich Gauss (1777-1855), Georg Simon Ohm (1789-1854), Gustav Magnus and Henri Victor Regnault. In fact, Regnault's penchant for accurate measurements led him to build his own measurement apparatuses (thermometers, pycnometers, volumenometer, dew point apparatus …) and sometimes to perfect very curious machines (respiratory apparatus…). The aim of performing accurate measurements was to produce useful data as a basis for empirical generalization, thus attempting to solve theoretical problems. But the goal was not only to make the measurements controllable but also to design basic measurement methods free from any theoretical interpretation. He transmitted his stubborn will for performing accurate measurements to his disciple William Thomson, who followed the same path.

Prior to his famous campaign to measure the steam properties, in 1825 he developed the first psychrometer, a tool for measuring humidity. It was based on some observations: when a piece of muslin was moistened with water, wrapped around a thermometer and then exposed to atmosphere, evaporation and cooling occurred and an indication of the cooling temperature was obtained. The psychrometer designed by Regnault was composed of two thermometers whose temperature scales matched and placed side by side. The bulb of one thermometer was fitted by a sleeve of cotton soaked with distilled water. A flow of air was imposed over the thermometers, which induced the evaporation of water from the wet thermometer. Its bulb was thus cooled until a thermal equilibrium was reached. By monitoring the temperatures of both thermometers, humidity measurements could be deduced easily. To validate its results, he compared them with many cares to the chemical method. As usual he considered the influence of all parameters: dry or saturated air, closed or opened rooms, inside or outside (Regnault 1845, Jamin 1859).

Regnault studied the whole subject of thermometry critically with the constant care of identifying all sources of error. His aim was to find a thermometer for which a change in temperature was proportional to the heat added to it and capable of measuring temperatures accurately. Using his results on the dilatation of gases, he substantially improved the air thermometer of Dulong and Petit. He showed that, when the air inside the thermometer was at different pressure levels, the temperatures measured remained exactly the same. He changed also the nature of gas. If air was replaced by another gas like hydrogen, carbonic acid or sulphurous acid, some differences could appear. Afterwards he modified the reservoir to see if using a reservoir made in glass or in crystal might change the results. But they did not. Finally, he compared the results obtained by air thermometer and mercury thermometer. For high temperatures, he showed experimentally that the measured value depended strongly on the purity of glass when using mercury temperature (Regnault 1842b, Jamin 1859). Thus, the gas thermometer was at that time the more accurate way for determining high temperatures and could be based either on constant pressure or on constant volume. Later, he obtained also very accurate temperature measurements with the constant volume hydrogen thermometer, which was then standard.

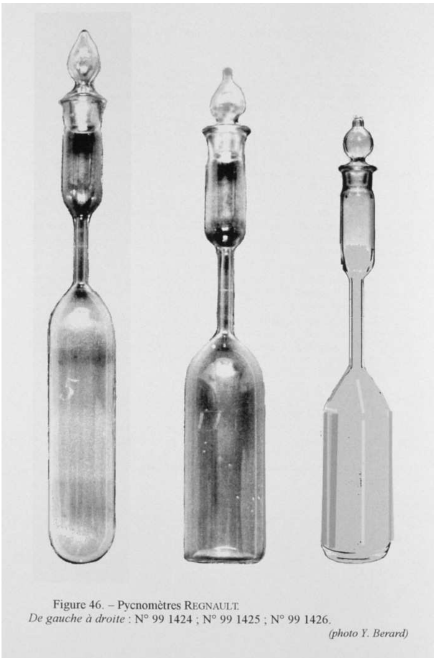

Figure 3: Pycnometers designed by Henri Victor Regnault (picture of Y. Berard, Oceanographic Museum of Monaco, NOAA Collect).

In 1843, he was the first to design pycnometers, whose three examples are presented in Figure 3. These instruments were used to measure the density of liquids. Regnault compared the use of pycnometers with other apparatuses like the hydrostatic balance. In the same way, he developed also the specific gravity bottle: the liquid inside the bottle, whose volume and mass are perfectly known, was weighed and its density was then calculated. He designed also other apparatuses to measure accurately the density of gases and vapours (Jamin, 1859).

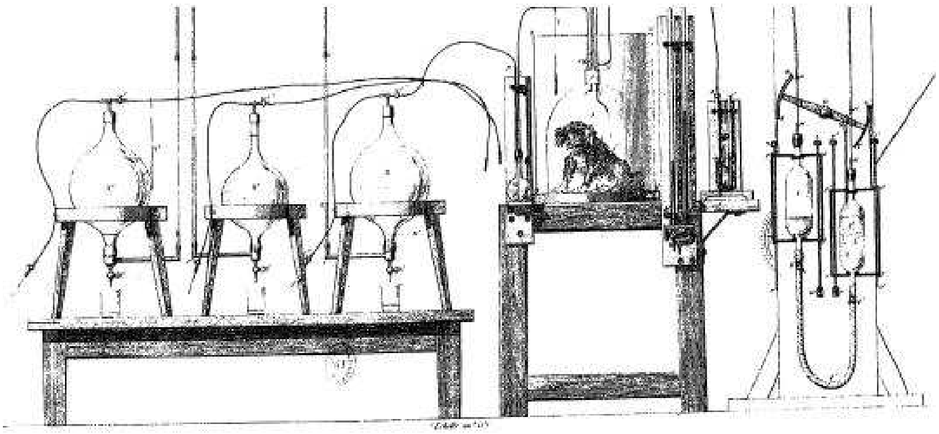

Figure 4: The respiratory physiology apparatus of Henri Victor Regnault and Jules Reiset (1849).

During the 19th century, the human body was seen as the most complicated but interesting heat machine. Justus Von Liebig studied the chemical balance in animals in order to determine the nutritional values of some food products. Regnault had worked under the guidance of Von Liebig in Giessen, and in 1849, with the help of Jules de Reiset, he perfected the respiratory calorimeter shown in Figure 4. Thanks to this machine, it was possible to assay respiratory gas exchange of small animals over extended periods. This technique known today as the Regnault method has been adapted later to aquatic animals. In this closed loop apparatus, oxygen was supplied to the dog by a tube on the left and carbon dioxide was removed by the tubes on the right. The respired air was passed through an absorbent to remove the carbon dioxide and then returned to the respiration chamber to be used over again. Oxygen was supplied as needed to replace that taken up by the animal. Thus, the oxygen consumed was measured directly by the quantity required to maintain constant pressure in the system. The amount of carbon dioxide given off was obtained by weighing the absorption vessels or by titration. Some instruments for measuring temperature and pressure changes were also placed in the chamber. From their experiments, they drew some conclusions: if the animal has a vegetarian diet, he transforms more oxygen into carbonic acid. They noticed also that one part of the oxygen has been used to transform foods into uric acid… This part is more important if the animal eats more meat or grease. The last observation was that if the animal is sick or voluntarily hungry, it absorbs nitrogen instead of exhaling it.

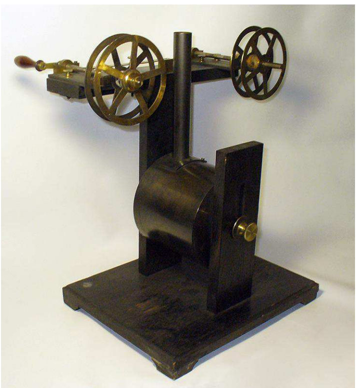

Figure 5: Regnault's chronograph.

When Regnault studied the specific heat of gases, he was aware that the ratio of the specific heats of gases (the coefficient γ) depended strongly on the speed of sound. An accurate determination of the speed of sound was the promise of a better understanding of the molecular constitutions of gases and of the laws governing their behaviours. Convinced that the early measurements performed since 1677 were inaccurate, Regnault designed in 1868 an apparatus for determining the speed of sound, capable of accurately measuring time intervals to fractions of a second. Reels of 2 cm wide paper tape were prepared by cranking them over a smoky camphor candle (Figure 5). The sooty paper tape was then placed in the chronograph so that marks from three metal styli could be scratched onto the smoked surface. One stylus, attached to a standard electrically driven tuning fork, laid down a continuous trace of a sine wave. The other two styli were driven by electrical on and off signals. The time interval between the on and the off signals was easily determined by counting the number of sine waves between them. The method was thus independent of the rate at which the paper was cranked through the device. In underground tunnels of Paris up to 5 km long, he ran wires to carry electrical signals from a sound producer and a sound receiver to his device. This apparatus found many other applications. In particular, it was used to quantify the effects of small doses of chloroform and ether on the rapidity of nervous and mental processes (Coats et al. 1879). Between the 12th of November 1862 and the 14th of July 1866, he measured the speed of sound in air and five other gases. He confirmed that the speed of sound in gases is independent of pressure but it decreases with distance and is proportional to the diameter of the tube used.

Regnault's skill in developing his own measurement apparatuses in all fields of chemistry, and most of all of physics, led him at the end of his career to strongly advocate for the use of the best instruments to measure pressure, temperature, hygrometry and quantity of carbonic acid for meteorological purposes. For example in 1862, he published a paper on the apparatuses to use to measure temperature and pressure in the different atmospheric layers (Regnault 1862). In his paper of 1871, he proposed to use the basin barometer for measuring barometric heights. He compared also the advantages and disadvantages of air thermometer, liquid thermometer and thermo-electrical thermometer for example. In the same volume, he wrote another memoir on a new gas manometer, highly accurate and dedicated to high pressure measurements in gases (Regnault 1871b).

Henri Victor Regnault, the photographer (1841-1872)

Many French scientists of Victor Regnault's generation experimented with photography, but Regnault was unusual in his ability to move seamlessly between the new medium's distinct provinces of science, art, and industry. This is undoubtedly why his peers elected him as the first president of the Société Française de Photographie (SFP) in 1854, an organization founded with the explicit mission of advancing photography into these three spheres of modern life.

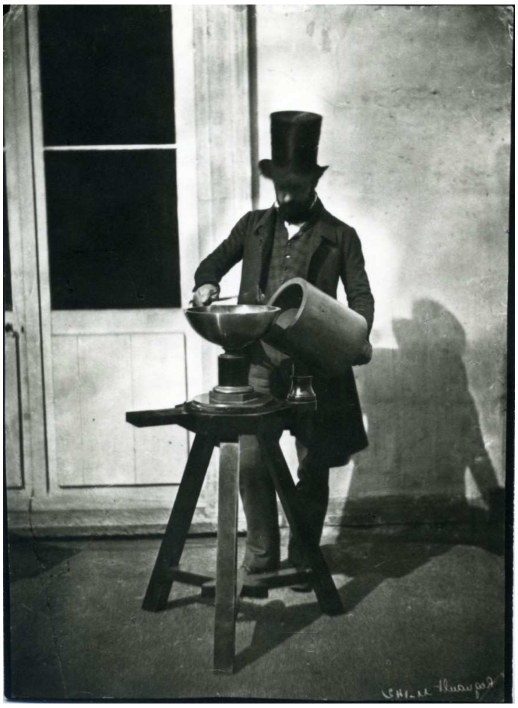

Figure 6: Henri Victor Regnault, Acoustic Experiment, calotype, c. 1850. Société française de photographie, 473.142.

The full extent of Regnault's photographic practice will probably never be known; what remains today is the image of a man captivated by the promise of photography and committed to its progress, pieced together from bits of correspondence and documents from the SFP. One additional resource remains beyond these textual fragments: over two hundred negatives made by Regnault between 1848 and 1855. And although the majority of Regnault's images show him employing the camera in the typical manner of the "gentleman amateur," that is, using it in leisure hours to make family portraits and artistic images, it is significant that Regnault felt compelled to justify his photographic activities as a supplement to his scientific research. The photography in Figure 6 shows for example an acoustic experiment of Regnault.

First experiments with photography

As a visual record of time elapsed, photography was naturally regarded by scientists of that empirical age as a discovery of tremendous importance, with the eminent physicist, Jean-Baptiste Biot, remarking that Daguerre had done nothing less than place an "artificial retina" in the service of science. It is not known exactly when Regnault first took up photography, but by 1841, he was already significantly involved in the emergent medium. In that year, Biot received sensitized paper and instructions for its use from the English photographic inventor William Henry Fox Talbot, which he passed along to Regnault, assuring Talbot that Regnault would turn a better hand to Talbot's new "calotype" process, since he was already proficient with the daguerreotype. Still, it is likely that Regnault's photographic work in the early 1840s was fitful, as these were the frenetic years that opened his galloping career in science. Noticed early on as one of the most promising students of his class at the École Polytechnique, Regnault had already been elected to the Académie des Sciences by 1840, at the impossibly young age of 29. From his adjunct professorship at the École des Mines in 1839, he moved to a dual appointment at the École Centrale des Arts et Manufactures and the École Polytechnique in 1840, and by 1841, he had left these positions for the chair in physics at the Collège de France. Yet he still found some time for photography, for the record shows him practicing calotype photography with other neophyte photographers in the 1840s, like the English amateur Calvert Jones and the French photographic inventor Hippolyte Bayard (Kraus 1990). The Comptes rendus of the Académie des Sciences also record the frequency with which Regnault was asked to test the many photographic improvements brought before the Academy in the 1840s. One of the most significant of these was presented by Louis-Désiré Blanquart-Evrard, an inventor from Lille who brought forward an improved paper photography process that ultimately succeeded in outflanking the stifling patents Talbot had placed on paper negative photography. In 1847, Regnault chaired the academic committee that examined Blanquart-Evrard's process, and it is possible that this experience inspired his subsequent surge of photographic activity.

Photography's foremost technical expert

The year 1851 was a seminal year for photography, marking the point at which a basic institutional and commercial superstructure came together to support the growth of photography, and Regnault was at the center of those developments. In that year, he joined with other scientists, artists, and illuminati to form the first photographic society, the Société Héliographique, a rarified circle that met informally over dinners to discuss the latest details of the new medium. One by-product of the Société was La Lumière, Europe's first photography journal, also launched in 1851. In its first few years of publication, we find frequent mention of Regnault's photographic activities, including such things as his discoveries for a method of chemically reducing photographs to line drawings, the use of pyrogallic acid as a developer, and the use of the vacuum pump in sensitizing paper. La Lumière also carried reports of the Société Héliographique meetings, which reveal

Regnault's position as the recognized expert in all scientific and technical matters. Indeed, his double expertise in chemistry and physics made him the leading authority on matters involving both chemistry and optics, and he would remain photography's leading technical expert well into the 1860s. One recalls that this early era in photography fostered multiple photographic processes—the daguerreotype, the calotype, the collodion wet-plate, to name the three most common—and Regnault worked with them all.

Only two instances of Regnault's work having been exhibited in public, in 1852 and 1853, when his friend John Stewart placed his own collection of Regnault's landscapes in photographic exhibitions at the London Society of Arts. Writing on the first SFP photographic salon in 1855, Paul Périer remarked on Regnault's self-imposed absence from the artistic ranks when he described him as "our excellent and illustrious President, who in his rare hours of leisure makes prints of the first quality, known to too few privileged persons, but who … speaks to us of art, as if he never had any other religion, and as if he was not also one of the champions of European science" (Périer 1855).

Artistic work in photography

Eventually, Regnault's own photography was quite forgotten and his substantial body of photographs was simply mistaken as his personal photography collection. As we now know, Regnault was not simply the technical expert at the center of a circle of artist-practitioners; he was their equal as an image-maker, and despite whatever sensibility kept him from exhibiting in the photographic salons alongside them, he was as artistically motivated in the execution of his photographs as his peers.

Figure 7: Henri Victor Regnault, Eugène Regnault asleep, calotype, c. 1852. Société Française de Photographie, 473.21.

Regnault's earliest series—about 150 portraits—were made between 1848 and 1852. Dozens of these images portray his wife, children, and extended family (Figure 7), and they comprise what may be the most extensive group of family portraits of this early era. Compared with the formality of most early photographs, these family portraits are surprising in their intimacy and sense of play. The calotype process was slow by modern standards, with exposure times between 10 and 30 seconds; to capture a "living" image was therefore the aspiration of good photographers. To photograph his children while simultaneously holding them still and retaining a sense of animation, Regnault experimented with clothes, affectionate poses, placing the younger children in the lap of his wife or eldest son, or even photographing his youngest child asleep in his crib. Moreover, photographing in natural, ambient light, Regnault achieved a naturalism that looks entirely different from the predictably controlled sky-lit portraits made by the professionals of the period. So while the pictures made at these lengthy sittings could not be called spontaneous, their vitality would rarely be matched before 1880s, when flexible film and simplified cameras ushered in the snapshot era.

Around 1850, Regnault also began making dozens of portraits of his associates at the Institut and the Collège de France. These sittings took place outside of his office, where he appears to have caught his colleagues coming to and from lectures and meetings, inducing them to sit for a portrait. There is an offhand air about these images, as well; the range of poses and demeanors suggests Regnault allowed the sitters to arrange themselves. The brilliant physiologist Claude Bernard faces the camera with formidable ferocity, the Saint-Simonist economist Michel Chevalier gazes past the camera, seated in prim self-composure, and the orientalist Jules von Mohl sits with top hat, a roll of papers, and umbrella in hand, ready to move on to his next appointment. Many of these sitters are still unidentified, but we can be sure they belonged to Regnault's academic cadre.

By 1852, Regnault had graduated from the small (approx. 18 x 22 cm) camera he used for portraits to a large (approx. 33 x 43 cm) camera for landscapes. The stimulus to photographing landscape was surely his relocation in that year to the small town of Sèvres, just west of Paris across the Seine (Figure 8), where he had been sent by the government to direct the state porcelain factory. Regnault had quickly realized the burdens of his administrative position, and between his struggles with the Emperor's minister and the factory's nearly 200 employees, he was miserable enough to submit his resignation in 1853—which the Emperor declined to accept. One is tempted to believe that his photography became a respite from work—one of the compensations of living at Sèvres. Stealing time from his factory obligations, he took his large view camera and its heavy tripod into the ancient forests, gardens and allées of the nearby Parc de Saint-Cloud and to the farms and dwellings along the river's edge, producing several dozen atmospheric landscapes in the manner of Barbizon artists, several of whom lived nearby and occasionally visited the factory. Regnault's early morning views made along the river are remarkable for their sense of tangible light and atmosphere, which has led at least one art historian to describe Regnault as "proto-impressionistic" (Heilbrun 1984). At other times, he photographed on the extensive factory grounds, making architectural studies, rustic still lives, and even genre studies of the factory's population at work and at rest.

Figure 8: Henri Victor Regnault, Banks of the Seine near Meudon, calotype, c. 1852. Société française de photographie, 473.177.

Decline in photographic work

There are many frustrating gaps in the record of Regnault's photographic life, but the greatest mystery may be why he maintained his photography as a private avocation and chose to stay behind the scenes as the technical expert, while his SFP colleagues took full advantage of the burgeoning photographic salon culture in Europe. In the early 1850s, La Lumière reported Regnault's participation at the frequent "photographic soirées" hosted by prominent figures in the small world of artistic photography, at which he would have shared his latest work, yet he purposely stayed out of the public view as a photographer, even declining to show work in the SFP's annual salon.

Two clues to this reticence are found in a pair of letters, the first addressed to his mentor and friend, the German chemist Justus von Liebig, with whom he had studied in the 1830s. Regnault's 1851 letter concerned a portrait he had made of Liebig, and included this curious comment: "I am devoting myself to this art, not for amusement, but because I am shooting a great part for the drawings in my work on Physics," an assertion that he involuntarily contradicted by adding "When the weather improves a little, I will make my own portrait and send you one" (Regnault 1851a). This assertion illuminates Regnault's conflicted motivations, especially when we consider that only a handful of photographs related to his scientific work (ten photographs of staged acoustic experiments) are known to survive, compared with more than 200 extant works of landscape, portraiture, and still life. One further comment, made to the scientist Sir John Herschel, gives further insight to Regnault's ambivalence. In a letter of 1851, Regnault described Herschel’s brother-in-law, John Stewart, who had recently taken up photography: “Several times I have received news of Mr. Stewart, who definitively possesses this fatal passion for photography; he surrenders himself to it with the ardor of a new husband, and I don't doubt that he will obtain good results. As for me, I reproach myself everyday for the time I spent with it, and that I should have used to finish the works which have absorbed me for several years" (Regnault 1851b). The reader can refer to the recent book of Dahlberg (2005) for more details about the legacy of Regnault in photography.

His most ambitious landscapes were still before him when he wrote this, but Regnault increasingly found that his duties at the Manufacture de Sèvres, his state-commissioned scientific research, and the demands his large family left no room for photography. He would continue to direct the SFP until 1868, but his own photography seems to have tapered off after 1855. And while he set the practice of photography aside in order to concentrate upon his scientific work, it seems he always intended to go back to it. In a letter dated January 19, 1870, his son, the celebrated artist Henri Regnault, urged his father to visit him in Morocco with promises of photography: "I hope you'll come see me here next autumn. You can do photography and go hunting with Lagraine: every evening you'll return with a dozen hare and partridge, and a dozen negatives!" (Duparc 1872). Sadly, the Franco-Prussian War intervened, and exactly one year later Henri was killed on the battlefield of Buzenval, an event that cast the end of Regnault's life in deep shadow. With his family shattered and his once-brilliant career passed over by shifting scientific currents, Regnault, his scientific legacy, and his photography fell into obscurity. He died on January 19, 1878, on the seventh anniversary of Henri's death.

Conclusion

Regnault's photography was quickly forgotten after his death. In fact, the emphasis on his role as a technical expert and not as one of the artists of the medium—an image he clearly helped create—is responsible at least in part for the fact that Regnault has been systematically overlooked in the international rediscovery of early photography that began in the 1970s. Given that this reassessment took place in the art world, it is perhaps not surprising that curators, dealers and collectors first combed the literature and archives of early photography for those who were recognized as artistic photographers in their own time, whereas Regnault appears to have actively avoided participating in exhibitions and otherwise accepting the public role of an artist of the new medium. Happily, his contributions to the history of early photography as a leader, a technical expert, and an artist, have begun to be recognized by a new generation of scholars and curators in the past ten years (Dahlberg 2005).

As for his legacy as a scientist, compared to his contemporaries (Hermann Helmholtz, Julius Von Mayer, James Prescott Joule, William Rankine, Rudolf Clausius, James Clerk Maxwell…), Henri Victor Regnault rapidly sank into oblivion. One finds some possible explanations in the discourse of de Lapparent (1897) or in the review of Fox (1971). De Lapparent (1897) claimed in his tribute to his colleague that: « *Regnault a été un grand* *savant. Il eût paru plus grand encore si, moins sceptique au regard des théories, il avait appliqué son génie, soit à développer ce que contenaient en germe ses belles recherches sur les éthers, soit à faire sortir de ses expériences l'équation caractéristique des fluides, soit à ne se laisser devancer par personne dans l'établissement des lois de la Thermodynamique*. » He regreted also that Regnault transmitted his knowledge to only very few students even if he was the mentor at the École Polytechnique of a prestigious student, William Thomson. Robert Fox (1971) drew the same conclusion. According to him, the 1830s marked the end of the French supremacy in physical sciences and the results of Regnault, which were only an « *unimaginative quest for unimpeachable numbers* », appeared to be less important than those of Laplace for example. Clifford Truesdell (1980) went much further by presenting some of Regnault's experiments in his book, in a chapter entitled "The Disastrous Effects of Experiment upon the Development of Thermodynamics, 1812-1853", by considering the work of Regnault as a brake for progress in thermodynamics. Finally, Le Chatelier (1911) pointed out also that the memoirs of Regnault were somewhat difficult to read.

Considering his fruitful career in retrospect, the explanations of Le Chatelier (1911), Fox (1971) and Truesdell (1980) are knockers. In spite of all the misfortunes which haunted his life (the deaths of his parents when he was eight, the deaths of his wife and of his son and all his problems of health), Henri Victor Regnault left behind him major discoveries in chemistry (law of substitutions, PVC…) and numerous laws in thermodynamics (latent heat of vaporization of water, specific heat of gases, liquids and solids…) deduced from a huge amount of very useful and accurate data. He improved the value of the absolute zero temperature and published, in 1847**,** an early version of the perfect gas law. He developed many methods for performing accurate measurements in the fields of acoustics, chemistry and most of all thermodynamics, which were rapidly accepted as superior to any existing approaches. This also was the opportunity for him to design new and sometimes exotic apparatuses: psychrometers, thermometers, hygrometers, pycnometers, chronographs, respiratory apparatuses… The French chemist Marcellin Berthelot (1827-1907) regarded him as the "personification of the genious of precision". It is corroborated by many other marks of sympathy by Dumas or Arago among others. Regnault published also his famous *Cours élémentaire de chimie*, which became a best seller during the 19th century and which was the first book specially written for teaching. Thus, the legacy of Henri Victor Regnault in chemistry and thermodynamics is huge and for that reason, we should hope that his meaning for the students of today would not only be the universal gas constant *R* contained in the perfect gas law.

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